IN THE MATTER	of the Resource Management Act 1991
AND	
IN THE MATTER	Lake Rotorua Nutrient Management – **PROPOSED PLAN CHANGE 10** to the Bay of Plenty Regional Water and Land Plan
BETWEEN	DairyNZ Limited
AND	Bay of Plenty Regional Council

STATEMENT OF PRIMARY EVIDENCE OF DR. THOMAS STEPHENS FOR DAIRYNZ LIMITED

22 FEBRUARY 2017

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1. INTRODUCTION

1.1 My full name is Thomas William Stephens.

1.2 I hold a BSc (First Class Hons) degree in Geography (University College London), a Masters (Distinction) in Freshwater and Coastal Sciences (University College London, Queen Mary University of London) and a PhD in Geography (Commonwealth Scholar, University of Auckland).

1.3 I have more than 10 years of international and national experience in fresh water science, principally in the field of palaeolimnology (the reconstruction of environmental changes attributed to land use and climatic effects on water quality). My expertise in freshwater science is founded on knowledge of hydrology, aquatic geochemistry (elemental, stable and radiogenic isotopes) and biology (fish, invertebrate, macrophyte and algal ecology).

1.4 I have been employed as a *Water Quality Specialist* at DairyNZ ("DNZ") since November 2012. I project manage and directly contribute to the delivery of water quality science with Crown Research Institutes and tertiary research centres around lakes, wetlands, rivers and aquifers affected by dairying in New Zealand. Recent evidence of technical expertise in water quality includes co-authored reports: (1) analysis of the sources and historical changes to sedimentation from the Waihou-Piako rivers (in collaboration with the Waikato Regional Council and National Institute of Water and Atmospheric research)[1]; (2) recommendation of freshwater management units for Northland (for Northland Regional Council)[2]; and (3) reconstruction of past water quality histories in Northland dune lakes (for Northland Regional Council)[3]. In 2012, I analysed trends in water quality for Lake Rotorua during the period 2001-2012 at the request of Deputy Environment Commissioner David Kernohan in collaboration with the University of Waikato and on behalf of the Lake Rotorua Stakeholders Technical Advisory Group[4]. Most recently, I have taken an expert advisory role to the Sustainable Farming Fund "P-project", advancing on-farm phosphorus mitigation in the Rotorua catchment through detainment bunds.

1.5 Prior to joining DNZ, I was a post-doctoral research fellow at the University of Florida (USA) involved in the development of a statistical tool for establishing nutrient limits in lakes throughout the State of Florida from empirical evidence of regional algal-nutrient relationships. This research was conducted for the Florida Department of Environmental Protection and United States Environmental Protection Agency as part of a revision to the Clean Waters Act. My responsibilities included the design, collection and statistical analysis of water quality data, including determination of algal-nutrient relationships. I have since co-

[1] Swales et al. (2016)
[2] Hughes et al. (2016)
[3] Rip et al. (2016)
[4] Abell et al. (2012)

authored two reports on recommended nutrient guidelines in Florida, for the Florida Department of Environmental Protection.

1.6 Earlier doctoral experience involved reconstructing changes to water quality and environment over the past 50,000 years at Lake Pupuke (Auckland). During this time, I worked in collaboration with the British Geological Survey, University of Lancaster, University of Swansea and Natural Environment Research Council (2006-2011). This research involved the analysis of present-day algal dynamics and the empirical demonstration of past changes to water quality arising from climatic and land use change around the crater maar lake.

1.7 I have been authorised to provide expert evidence on behalf of DNZ and Fonterra Co-Operative Group Limited, on water quality science underpinning management to a Trophic Level Index ("TLI") of ≤4.2 in Lake Rotorua, through the Proposed Plan Change 10 ("PC 10") to the Bay of Plenty Regional Water and Land Plan.

Background

1.8 My involvement in PC 10 commenced in January 2017 when I was asked to review and respond on behalf of DNZ and Fonterra Co-Operative Group Limited.

1.9 To date, my involvement has included analysis of reported water quality, reviewing water quality modelling and applying lake nutrient theory, particularly in regards to whether the approach taken by PC 10 is supported by local monitoring data and scientific principles for adaptive lake management.

Code of Conduct

1.10 I confirm I have read the Expert Witness Code of Conduct set out in the Environment Court Practice Note 2014 and agree to comply with it. I confirm that this evidence is within my area of expertise, except where I state that I am relying on the evidence of another person. I have not omitted to consider material facts known to me that might alter or detract from the opinions expressed in this evidence.

1.11 I am authorised to provide this evidence for DNZ and Fonterra.

1.12 In preparing this evidence I have read proposed PC 10, the DNZ submission, and the following Statements of Evidence:

(a) Mr. Andrew Bruere (Council)
(b) Prof. David Hamilton (University of Waikato)
(c) Dr. Kit Rutherford (NIWA)
(d) Section 32 and 42A reports (Council)

2. SCOPE OF EVIDENCE

2.1 I limit my evidence to supporting the need for a comprehensive science review to implement an adaptive nutrient management approach in PC 10, enabling the Bay of Plenty Regional Council ("Council") to manage and protect water resources to a TLI of 4.2, whilst accommodating change to our understanding of algal-nutrient dynamics in Lake Rotorua.

2.2 Specifically, I address the need for the proposed review of limit-setting science (LR M2 & M3) following changes in scientific understanding of nutrient-algal dynamics in Lake Rotorua. Simply, that the lake response to aluminium sulphate ("alum") dosing has achieved the Regional Water and Land Plan Objective 11 (TLI ≤4.2) under markedly different nutrient loading mechanisms than expected, as noted by Prof Hamilton in his statement of evidence (paragraphs 12 & 15).

2.3 My evidence should be read as largely supportive but independent of that outlined by Dr. Rutherford, Prof. Hamilton and Mr. Bruere. I do not comment on the risks nor appropriateness of continued alum dosing as this is already covered by Prof. Hamilton and Mr. Bruere.but I do comment to highlight disagreement with both regarding their certainty and rationale for prioritising managing nitrogen ("N") over phosphorus ("P") as the most effective approach to achieving a TLI ≤4.2.

3. EXECUTIVE SUMMARY

3.1 Lake Rotorua has experienced a consistent improving trend in the Lake Tropic Level Index ("TLI") since 2003, preceding low-level alum dosing to the Utuhina (2006+) and Puarenga Streams (2010+). Since 2012, lake health has oscillated about a TLI of 4.2 (±0.2)[5], required by the Bay of Plenty Regional Water and Land Plan, Objective 11.

3.2 Improving TLI at Lake Rotorua was disputed prior to 2012[6] and not predicted by in-lake modelling prior to revisions in 2015. Recently, in-lake water quality monitoring and revised modelling indicates the lake has become P-limited, largely due to alum dosing[7]. Algal production is now constrained by reduced P, both absolutely by mass and relative to N, resulting in reduced overall algal biomass ("Chl-a"). Hence a TLI ≤4.2 has been achieved in 2012 and 2014 despite external anthropogenic N loads to Lake Rotorua exceeding that required by Regional Policy Statement Policy WL 3B(c) (e.g., by a factor of x1.5)[8].

3.3 From this, fundamental questions remain of algal-nutrient dynamics in Lake Rotorua, including the mechanism behind TLI improving three years prior to alum dosing, potential for catchment mitigation and in-stream attenuation processes affecting land-derived nutrient loads to Lake Rotorua, whether alum "resetting" internal nutrient loading alters modelling outcomes, and whether P-management is more appropriate on the basis of effect, risk and cost than the focus upon N-management to achieve a TLI ≤4.2 recommended by PC10.

3.4 Given uncertainty in how Lake Rotorua will respond to future nutrient management and evidence that P-limitation is effective at attaining a TLI ≤4.2, I support a science review and implementation of adaptive management as set out in Method LR M2 and M3. In my opinion an important component of the science review, is research into P-management strategies, regardless of future decisions on attaining a TLI ≤4.2 under either continued P-limitation, or under the proposed co-limitation of P and N.

5 Scholes and Hamill (2016)
6 Abell et al., (2012) was called for under mediation of the operative Regional Policy Statement held on 21 November 2012 to resolve uncertainty about recent trends in TLI attributes
7 Hamilton et al. (2015)
8 Hamilton et al. (2015)

4. HAS LAKE ROTORUA ATTAINED ITS SUSTAINABLE WATER QUALITY TARGET – WAS THIS PREDICTED?

4.1 Lake Rotorua attained the community water quality target in 2012 with limited variation since (±0.2 TLI units[9]) but here, I demonstrate this was not predicted by in-lake modelling, nor considered in the approach underpinning derivation of the sustainable nitrogen load (435 tonne TN/yr).

4.2 The Lake Rotorua and Rotoiti Action Plan set out management actions to restore Lake Rotorua to a community-desired water quality state akin to that of the 1960s, through reference to a TLI of ≤4.2. The TLI comprises four attributes: clarity, total nitrogen and total phosphorus (TN, TP) and algal biomass (Chl-a). Clarity and Chl-a respond indirectly and directly respectively, to changes in TN and TP. So, the TLI is both a measure of water quality contaminant (TN, TP) and effect (clarity, Chl-a).

4.3 Lake research has emphasised that Chl-a (and indirectly clarity) typically respond to one or both of TN and TP[10]. Equally, that changes in TN or TP may not alter algal biomass when available to excess – reflecting the requirements of N and P by all living photosynthetic organisms in an optimal atomic ratio of 16:1 (TN:TP) to generate sufficient protein and genetic material, respectively for cell division[11]. Where a lake is P- or N-limited, reductions are typically recommended to that limiting nutrient to restrict algal biomass[12]. Non-limiting nutrient reductions are increasingly also recommended for N or P, even where a single nutrient strongly limits algal yield. This is done to manage acute risks of failing to restrict the limiting nutrient, or to manage uncertainty associated with spatial or temporal variation in nutrient limitation (i.e. as a precautionary approach)[13].

4.4 Trend analysis for Lake Rotorua demonstrates a consistent improvement in TLI since 2003, with most rapid improvement between 2010 and 2012[14]. All four TLI attributes at two monitoring locations improved by a statistically significant (p<0.001) and meaningful rate (>1%/yr) over the interval 2001-2012. TP improved most (by 8-9%/yr) with Chl-a responding by a near equivalent improvement (by 7%/yr). TN improved at half the rate of TP (4%/yr), causing TN:TP ratios to increase (6%/yr) and indicating greater probability of P-limitation of algal production. Clarity improved least (by 3%/yr) suggesting some impact of reduced algal blooms but that drivers other than nutrient availability are also important (e.g., resuspension of sediment). Trend analysis since 2012 also suggests stronger P-limitation has developed[15]. Trends over the most recent period (2010-2014) are less distinct owing to the

[9] Scholes and Hamill (2016)
[10] Schindler (1977, 2012); Elser et al. (2007); Jeppesen et al. (2007); Paerl (2008); Schindler et al. (2008); Sterner (2008); Lewis et al. (2008)
[11] Loladze and Elser (2011)
[12] Downing et al. (2001); Sondergaard et al. (2003); Jeppesen et al. (2005); Burger et al. (2007a)
[13] Elser et al. (2007); Wilcock et al. (2007); Moss et al. (2013); Paerl et al. (2011, 2015)
[14] Abell et al. (2012)
[15] Scholes and Hamill (2016)

shorter duration tested but, statistically significant improving trends were still noted in Chl-a, TP, TN and TLI (in decreasing order of magnitude from 12 to 1%/yr; $p<0.05$)[16].

4.5 The timing of reduced TP since 2003, but most markedly between 2010 and 2012, broadly coincides with alum dosing of influent streams (Utuhina since 2006; Puarenga since 2010) and evidence that alum has entered Lake Rotorua, where it has likely caused flocculation and removal of P from the water column and pore-waters to strengthen P-limitation[17]. Revisions to in-lake modelling have demonstrated that the recent reduction in TP is sufficient to have driven the decrease in Chl-a and reduction in TLI to ~4.2[18]. Notably, these revisions have not identified the cause for improved water quality three years prior to alum dosing[19], revealing uncertainty about a potentially important process governing water quality in Lake Rotorua.

4.6 Recent improving trends in TP, Chl-a, SD and TLI were not predicted by in-lake and catchment modelling upon which a TLI target of ≤4.2 was based[20]. Whilst understandable given the effects of alum in Lake Rotorua were inadvertent, those effects stress an underlying assumption that the lake would require co-limitation to achieve a TLI ≤4.2, to have been inaccurate.

[16] Scholes and Hamill (2016)
[17] Hamilton et al. (2015)
[18] Hamilton et al. (2015)
[19] Hamilton et al., (2012) in 2.8.1 (pg.19) exclude natural climatic causes stating "whilst globally there have been obvious warming trends for the 1960s to 2010, there appears to have been little change in air and water temperature of Rotorua and the lake". Figure 19 (pg.42) demonstrates the revised model poorly captured TLI variation from 2001-2004, including a reversal to lower TLI ~2003.
[20] Mechanisms for improved TP, Chl-a, TN and SD, largely through alum dosing effects, have necessitated revision of the in-lake DYRESM-CAEDYM modelling upon which a TLI ≤4.2 and supporting sustainable nutrient loads proposed by PC 10 are based (see Hamilton et al., 2015)

5. LAKE ROTORUA IS NOW STRONGLY PHOSPHORUS-LIMITED – HAS OUR UNDERSTANDING OF ALGAL-NUTRIENT DYNAMICS CHANGED?

5.1 Lake Rotorua has become strongly P-limited through reduced internal P-loading, which I demonstrate confirms earlier understandings of the importance of internal nutrient sources to algal production in Lake Rotorua, but revises knowledge of algal-nutrient limitation[21].

5.2 Whilst the recent improvement in TLI strongly indicates algal growth in Lake Rotorua is now P-limited (due to the markedly greater relative reduction in TP and Chl-a than TN since 2003), earlier consensus had emphasised N-limitation drove algal production in the 1960s[22] and co-limitation was required to achieve a TLI of 4.2. The Water Quality Technical Advisory Group sought to replicate this when setting a sustainable nitrogen load limit of 435 tonnes TN/yr and 37 tonnes TP/yr (and from which modelling was used to later estimate corresponding in-lake TN, TP, Chl-a and SD, from which A TLI ≤4.2 was set). Given recent improvement under P-limitation, that assumption would benefit from review.

5.3 Ongoing P-limitation of Lake Rotorua is quite surprising in light of past evidence from algal-nutrient research dating to the 1970s. This indicated Chl-a showed a consistent growth response primarily to N **addition**, suggesting the lake was N-limited[23]. More recent research suggested algae increase their Chl-a content under conditions of greater N-availability[24], again emphasising the importance of N-limitation for Chl-a. Although, the latter study also found total algal biovolume responded greatest to N and P additions (i.e. that co-limitation was most prevalent for overall biomass rather than Chl-a), and P-limitation was evident during stratified conditions only[25].

5.4 Despite a lack of empirical testing into the effects of P, N or P and N **removal** from Lake Rotorua, groundwater researchers in 2015 suggested P mitigation would be ineffective at controlling algal production due to high background (natural) P-loading and that a focus on N-management, specifically nitrate-nitrogen (NO_3N), alone should be the priority[26]. Recent algal-nutrient dynamics diverge from this position that NO_3N, would be required at co-limiting concentrations to achieve a TLI of 4.2 in Lake Rotorua. Indeed, although TN availability has decreased since 2003 this was an indirect consequence of reduced algal production under conditions of P-limitation due to alum-dosing (i.e., occurred despite rises in NO_3N and anthropogenic N-loading to Lake Rotorua)[27].

[21] Burger et al. (2005); Burger (2006)
[22] White and Payne (1978)
[23] White and Payne (1978); Vincent (1981); White et al. (1986)
[24] Burger et al. (2007a)
[25] Burger et al. (2007a)
[26] Morgenstern et al. (2015) recommended that lake managers should focus only on restricting external N loads to Lake Rotorua as “the only effective way to limit algae blooms and improve lake water quality in such environments is by limiting the nitrate load” (referring specifically to lakes with relatively high natural P-loading from geothermal inputs)
[27] Abell et al (2012). indicated increased NO_3N by 22-24%/yr from 2001-2012 (p<0.001) which more recently, in Scholes and Hamill (2016) has since arrested or become more variable. Scholes (2013) also demonstrated that 8

5.5 In 2016, lake researchers built the most complete understanding so-far of algal-nutrient dynamics and concluded, a drive for N-limitation would be ineffective and likely to degrade water quality by promoting cyanobacterial blooms[28]. Hence, I agree with Prof. Hamilton in his evidence (paragraph 15[l]) that N-management alone would be ineffective for managing cyanobacterial risk to Lake Rotorua, but would clarify his suggestion that both N- and P-management is needed. To effectively manage cyanobacteria risk, you would need to manage P **only if** you had otherwise created conditions of N-limitation[29], which is not the case now. Instead, P-limitation has led to reduced dominance of phytoplankton by heterocystous (N-fixing) cyanobacteria in Lake Rotorua since 2003[30].

5.6 In addition to refuting the recommendation for N-limitation, the 2016 study recommends co-limitation to attain a TLI ≤4.2 on the basis that: TN and TP performed equally well in predicting Chl-a over 2001-2015; past evidence for nutrient co-limitation; and, uncertainty about the ability to address anthropogenic P-loss (an uncertainty identified in 1989[31] that has not been resolved since – see Section 6). However even this, the most exhaustive review to date, failed to consider that:

(a) TLI is generated from average in-lake conditions, whose estimation is highly sensitive to maxima or peaks in algal production (e.g., blooms). Maximum Chl-a is more strongly associated with TP than TN[32]. For instance, consider that the objective in managing Chl-a is to reduce peak concentrations beneath some threshold of effect, not across the entire gradient of algal abundance;

(b) Simple linear regressions of TN or TP on Chl-a do not account for the interactive effects of nutrients (e.g., that the relationship of TN on Chl-a might perform as well as that of TP on Chl-a where TN and TP are correlated, despite only TP having driven Chl-a)[33]. Over the last 15 years, TN and TP will have been correlated given declines in both have occurred consistently, through reduced TP causing reduced organic-N production (i.e., lowering TN indirectly, despite equivalent or greater TN input). This error was recognised as surprisingly common by an international review into determining drivers of lake eutrophication[34]. Hence, the reviewers did

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of 9 inflowing streams to Lake Rotorua observed significant, increasing trends for nitrate-nitrite nitrogen (NNN) from 1992-2012 (0.3-2.3 %/yr) and 6 of 8 streams from 2002-2012 (0.1-1.4 %/yr). Scholes (2013:iii) concludes from weighted averaging of gauged inflowing streams that TN loading has increased over the past decade

[28] Smith et al. (2016)

[29] See Codd et al. (2005) and Dignum et al (2005) in Huisman et al. (2005)

[30] Smith et al. (2016 – Fig. 7)

[31] Rutherford et al. (1989:435) first acknowledged that co-limitation was to be preferred to a P-limitation approach in the absence of knowledge about whether sufficient anthropogenic P-loading could be reduced to establish P-limitation

[32] Smith et al. (2016)

[33] Smith et al. (2016 – Fig.5)

[34] Schindler (2012)

not robustly test for N, P or co-limitation, and their findings are refuted by evidence that the lake has become P-limited over the past decade[35];

(c) A lack of knowledge about the efficacy of P-mitigation is not evidence that P-mitigation would be ineffective.

5.7 Despite the 2016 review, a fundamental of algal-nutrient science remains uncertain in Lake Rotorua – whether P-limitation can **sustain** a TLI of 4.2[36]?

5.8 Robust evidence now exists that P-limitation can **achieve** a TLI of 4.2 in Lake Rotorua without reduction in anthropogenic N-loads, contrary to the Section 42 report (paragraph 34) which says "altering the focus from nitrogen to phosphorus alone would not result in the TLI being achieved" [37].

5.9 The basis for why alum dosing has rapidly caused strong P-limitation and reduced algal productivity to within a TLI ≤4.2 is more certain. Internal or legacy nutrient loads are the dominant source of P available to algae in Lake Rotorua[38]. Alum dosing has reduced external dissolved P-loads from the Utuhina and Puarenga Streams but more importantly, reduced internal TP-loads by flocculation with suspended P and restricting dissolved P release from sediments[39]. Hence, alum dosing has resulted in combined external and internal TP loads of 34.5 tonnes/yr, approximately that of the sustainable P-load and suggesting the latter is appropriate to sustain a TLI of ≤4.2[40].

5.10 The effects of alum dosing have also revised earlier findings by revealing P-limitation can occur outside of stratified conditions[41]. Despite this, only a single study by the University of Waikato in 2015 attempts to model alternative sustainable nutrient budgets in light of Lake Rotorua becoming P-limited and achieving a TLI ≤4.2. The report includes two scenarios of P-limitation, both involving no further mitigation of N-loading from that contributed today and where the calibrated model under-predicts improved TLI during conditions of stronger P-limitation (e.g., by 0.3 TLI units in 2012). If external P-loads were reduced to 23.4-30.3 tonnes TP/year, then even if N-loads rose from today's 642 tonnes TN/year to a projected 730 tonnes TN/year at steady-state (representing contemporary loading without

[35] See evidence of Prof. Hamilton (paragraphs 12[a] & S15[i]) and Mr. Bruere (paragraph 82) as well as my paragraph 4.4 previously

[36] The evidence of Prof. Hamilton (paragraph 15[k]) suggests attaining a TLI 4.2 with nitrogen loads well above the sustainable nitrogen load of 435 tonnes TN/yr, is probable when phytoplankton are P-limited and as evidenced in the lake's monitoring records for 2012 and 2014 (e.g., by 642-750 tonnes TN/yr)

[37] Council state in the Section 42 report (paragraph 34) that "altering the focus from nitrogen to phosphorus alone would not result in the TLI being achieved" referring to whether P-management should be prioritised. As above, P-limitation coupled to increased NO_3N availability clearly can achieve a TLI of 4.2 or less

[38] Burger et al. (2007b) identified internal sedimentary P-release as dissolved-P, occurred at rates at least three times greater than external inputs. Burger (2006) revealed dissolved-P release rate exceeded TP sedimentation and loss rate. Rutherford et al. (1984) found similar indications of internal loads being a likely substantive source to lake totals for both N and P

[39] Hamilton et al. (2015)

[40] Hamilton et al. (2012)

[41] Burger et al. (2007a) demonstrated that P-limitation was restricted to periods of stratification. Although likely the case under past conditions (~2006), those conditions did not consider whether future P-reduction could then drive P-limitation more broadly

groundwater lag), the TLI would be between 3.5 and 4. For clarity, those two scenarios equate to a reduction in external TP-loading of 38-52%, based on current estimates of TP loading to Lake Rotorua of 48.7 tonnes TP/yr[42]. Despite the proportional reduction in anthropogenic loading alone being greater than this, the point remains that under conditions of strong P-limitation, no change in contemporary N-loading is apparently required to achieve a TLI ≤4.2.

5.11 Unfortunately, by failing to include scenarios modelling the effects upon TLI of just a 43-64% reduction in anthropogenic loading (which is required to achieve the sustainable P-load without alum), the latest modelling does not address if the sustainable P-load is able to maintain P-limitation under conditions of N-loading above 435 tonnes TN/yr. Instead, those two prior P-limited scenarios included a 25% mitigation of anthropogenic P loads with ongoing alum dosing effects. I understand that PC 10 refers to managing phosphorus but does not attempt to achieve the sustainable P-load.

5.12 Another related cause of uncertainty, is whether alum applications can "reset" internal P-loading and be reduced in balance with greater external P-management to ensure continued P-limitation and reduced organic matter (algal) production into the future (i.e., recognising there is uncertainty about risks from long-term alum dosing)[43]. That reduction in algal production has contributed to decreased benthic anoxia and reduced internal P-recycling from lake sediments (as well as greater N-removal via denitrification), in a positive feedback loop[44]. There is uncertainty whether reduced internal nutrient release should revise modelling assumptions about nutrient processes and the forecast timing of changes to nutrient availability (i.e., potentially bringing forward dates projected to achieve a TLI ≤4.2, whether under a P-limited or co-limited state).

5.13 My evidence and that of Prof. Hamilton indicate that although a P-limited state can attain a TLI ≤4.2 in Lake Rotorua, catchment and in-lake modelling also suggest a co-limited state can achieve the same TLI. The difference between them is the former is certain given recent P-limitation has induced a TLI ≤4.2, whilst co-limitation is probable from a reliance upon modelling rather than directly monitored observation.

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[42] Hamilton et al. (2012); Tempero et al. (2015)

[43] Alum tends to mineralise into a precipitate that becomes engrained with sediment restricting P-release from deeper internal sources, essentially resetting internal loading rates to that under the current conditions of limited organic matter production and therefore, lesser internal loads above the alum horizon (e.g., Welch and Cooke, 1999; Gibbs, 2015). The introduction of alum to Lake Rotorua raises the potential for this effect to alter the reduction in external anthropogenic loading required to less than 43-64%, through a staged reduction in alum and increased external P-management, that continues suppression of algal-production to current levels. Scholes (2013:34) raises this possibility to Council. Researchers have also raised this issue of internal barriers to P-loading being 'reset' by inactivation and that in eutrophic lakes, that without such inactivation, reductions in external loads were unlikely to be sufficient to drive improvement for the long-term (e.g., Welch and Cooke, 1999; Sondergaard et al., 2007; Huser et al., 2016). As to risks arising from short-term alum treatment of the Puarenga and Utuhina Streams, this has been described as minor by Tempero (2015) and Gibbs (2015). Despite limited alkalinity, additions are comparatively low by international standards, the range of pH within Lake Rotorua should preclude Al-toxicity from alum, and that the extreme scale of blooms needed to otherwise generate pH <4.5 or >8.5 in lake sediment is highly unlikely.

[44] Hamilton et al (2015)

6. UNDERSTANDING PHOSPHORUS MITIGATIONS IS CRUCIAL FOR MANAGING LAKE ROTORUA

6.1 Here, I demonstrate a lack of evidence about P-management has guided the decision by Council to prioritise N-management in PC 10. That without robust science on P-management strategies specific to Lake Rotorua, a science-based decision on whether to prioritise N and/or P-management cannot be made. Then, the lack of science risks failing to achieve a TLI ≤4.2 whether by P- or co-limitation as both require reduced P-loading to Lake Rotorua, and worse, promote toxic cyanobacterial blooms.

6.2 Mr. Bruere identifies that the focus of PC 10 is upon reducing N (paragraphs 34 & 38) due to the "challenging" nature of controlling for anthropogenic P-loss (i.e., that a 43-64% or 10-15 tonne TP/yr reduction in anthropogenic loads is required for a TLI ≤4.2)[45]. In his evidence, Prof. Hamilton (paragraph 15[l]) also identifies that high background (natural) inputs of TP "limit" the Council's ability to manage P in Lake Rotorua without alum dosing, acknowledging the 43-64% reduction in anthropogenic P-losses otherwise required[46].

6.3 Mr. Bruere (paragraphs 34 & 38) identifies P-mitigation strategies have been poorly researched, with limited effort to date investigating the opportunity to mitigate external loads, their costliness nor their cumulative effect towards achieving the sustainable P-load. For instance, empirical evidence of nutrient mitigation by Rotorua pastoral farms is limited to understanding the effects upon P-loads of actions to reduce N-loss[47], when N and P losses occur through fundamentally different processes (i.e. sub-surface and surface pathways, respectively[48]). Only general information on the effectiveness of dedicated P-management strategies has been produced for Council (in 2010), highlighting strategies that can yield a 43-65% reduction in anthropogenic P-loads[49]. Neither the suitability of these mitigations to the catchment, nor their specific efficacies have been reliably determined. That prevents my determining if they carry less cost, risk or greater potential than a focus on N-management.

6.4 Failing to achieve either balanced or greater reductions in P than N increases the risks of cyanobacterial growth in Lake Rotorua where cyanobacterial biomass is strongly driven by TP[50]. For instance, since 2003 cyanobacterial biomass has declined nearly a thousand-fold and shifted to non-toxic species under stronger P-limitation[51]. Hence, I agree with Prof. Hamilton in his evidence (paragraph 15[j]) that any reduction of TN-loading requires

[45] From Tempero et al., (2015) but note concern in my paragraph 5.12 previously that this might be an over-estimate given the potential for internal P-loading to have been "reset" by alum dosing
[46] Tempero et al. (2015)
[47] Evidence of Mr. Bruere (paragraph 38) states "further study is being undertaken to estimate phosphorus that will potentially be removed as nitrogen interventions are implemented, because changes in land use targeted for nitrogen loss reduction will also benefit phosphorus reduction to some extent"
[48] McDowell et al. (2013)
[49] See evidence of Ms. Muller (section 8) for discussion of P-mitigation effectiveness based on findings from elsewhere in New Zealand and produced for Council by McDowell (2010)
[50] Smith (2015)
[51] Smith et al. (2016)

proportionate or greater reduction in TP-loading to manage for cyanobacterial risks to water quality. However, as P-limiting and co-limiting P-loads are by principle the same[52] when Prof. Hamilton questions the ability of Council to manage P to a limiting concentration in Lake Rotorua (paragraph 15[l]), he is implicitly acknowledging that managing P to a co-limited TLI of 4.2 appears equally unlikely. Hence, whether managing for a future co-limited or P-limited Lake Rotorua, neither can be sustained at a TLI of 4.2 without our understanding how to reduce TP loads to ~37 tonnes TP/yr. Prof. Hamilton highlights this much in his statement of evidence (paragraph 15[l]) albeit without then drawing the link between a lack of knowledge about P-management efficacy or potential and the risks this could present of promoting increased cyanobacterial biomass.

6.5 To illustrate this point, if external N loads are reduced by 320 tonnes TN/yr without commensurate reductions in P-loading to 37 tonnes TP/yr, in-lake modelling suggests Lake Rotorua will become N-limited[53]. The N-limited lake is likely to support relatively more cyanobacteria, particularly N-fixing genera. Input of atmospheric-N by heterocystous cyanobacteria would then negate reductions in anthropogenic-N (i.e., the combined lake TN-load would exceed 435 tonnes TN/yr despite a 320 tonnes TN/yr reduction in anthropogenic N-loading). From the failure to achieve the sustainable TP load therefore, in-lake TP and TN concentrations would fail to achieve a TLI ≤4.2, also driving algal biomass (Chl-a) in excess of TLI ≤4.2.

6.6 Understanding how to reduce lake TP loads to ~37 tonnes TP/yr is fundamental to managing Lake Rotorua to a co-limited or P-limited TLI target. It remains uncertain however, if mitigation of anthropogenic P-loads can generate equivalent or greater reductions than alum has in achieving a TLI ≤4.2. Also if so, whether this will be at lesser cost, risk or need for land use change than the costs, risks and land use changes proposed by a focus on N-management in PC 10[54]. It is therefore important for the science review to determine the potential for, and efficacy of, TP-management strategies in the catchment.

[52] Jeppesen et al. (2003); Schindler (2012); Moss et al. (2013)
[53] Hamilton et al. (2012, 2015)
[54] See evidence of Ms. Muller (Section 5) for description of the significant costs to land holders for PC 10 implementation

7. CONCLUSION – IS A SCIENCE REVIEW INTEGRAL TO AN ADAPTIVE MANAGEMENT APPROACH AND RECOMMENDED FOR PC 10?

7.1 Council has indicated that adaptive management is at the core of implementing a strategy to manage Lake Rotorua water quality. My understanding of Policies LR P3 and P4 is that adaptive management of N is intended, but there is not the same intention for P management in PC 10.

7.2 The inclusion of P for adaptive nutrient management by PC 10 is warranted on account of robust scientific evidence for:

(a) P-limitation having recently arisen in Lake Rotorua under alum dosing;
(b) P-limitation having driven the lake to achieve a TLI ≤4.2 under increased NO_3N loading;
(c) A focus on N reduction alone increasing the risk of water quality degradation from increased incidence of cyanobacteria;
(d) The sustainable P load needing to be met irrespective of reductions in N loads, to result in co- or P-limitation at TLI ≤4.2.

7.3 However, the scientific evidence underpinning P-management is uncertain regarding, whether:

(a) Anthropogenic P-loads can be mitigated sufficiently to achieve P- or co-limitation of TLI ≤4.2 (i.e., the potential for and effect of P-strategies in the catchment relative to those of alum);
(b) Prioritising P-management would carry with it lesser cost or risk to the community in achieving a TLI ≤4.2 than the focus on N-management in PC 10.

7.4 Together this emphasises the need for an adaptive management approach that has the capacity to revise sustainable load estimates and prioritise N and/or P-management, in line with improved understanding of algal-nutrient dynamics and mitigation strategies. This will ensure maximum flexibility for the Council to achieve a TLI ≤4.2 of the operative RPS.

7.5 Accessing robust, evidence-based scientific input at 5-yearly intervals (e.g., reviews of trends in TLI attributes (LR M2a), progress towards the sustainable nutrient load limit (LR M2b), recalibration of predictive models (LR M2ci, cii, civ) and assessment of effects/ability for P-reduction (LR M2 cii)) will mitigate the uncertainties noted above, and permit evaluation of the cost-effectiveness for alternative approaches to sustaining a TLI ≤4.2 in Lake Rotorua.

7.6 Currently, there is simply no robust evidence of the potential for or benefit of prioritising a P-management approach to achieve a TLI ≤4.2, meaning there is equally, no firm evidence for an N-management approach being more cost-effective or risk-averse.

7.7 In conclusion, a lack of knowledge about P-mitigation hinders knowledge of whether N- and/or P-management is more appropriate for achieving a TLI ≤4.2 in Lake Rotorua. Of more concern, is that if Prof. Hamilton is correct to suggest P-management to a P-limiting concentration is unlikely, then a 320 tonne reduction in anthropogenic TN-loads proposed by PC 10 will likely degrade water quality further by promoting potentially toxic cyanobacteria dominance.

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8. REFERENCES

Abell, J., Stephens, T., Hamilton, D., McBride, C., and Scarsbrook, M. 2012. Analysis of Lake Rotorua water quality trends: 2001-2012.ERI Report No. 10. Report prepared in response to Environment Court mediation, 21 November 2012. Environmental Research Institute, University of Waikato, Hamilton.

Burger, D. 2006. Benthic-pelagic coupling of nutrients in Lake Rotorua. PhD Thesis, University of Waikato, Hamilton.

Burger, D., Hamilton, D., Pilditch, C., and Gibbs, M. 2005. Sediment phosphorus release during stratification in polymictic Lake Rotorua, New Zealand. *Verhandlung Internationale Vereingung de Limnologie*, **29**: 811-814.

Burger, D., Hamilton, D., Hall, J., and Ryan, E. 2007a. Phytoplankton nutrient limitation in a polymictic eutrophic lake: community versus species-specific responses. *Fundamental and Applied Limnology*, **169**: 57-68.

Burger, D., Hamilton, D., Pilditch, C., and Gibbs, M. 2007b. Benthic nutrient fluxes in a eutrophic, polymictic lake. *Hydrobiologia*, **584**: 13-25.

Codd, G., Lindsay, J., Young, F., Morrison, L., and Metcalf, J. 2005. Harmful cyanobacteria – From mass mortalities to management measures. In Huisman, J., Matthijs, H., and Visser, P. (2005). (Eds.) Aquatic Ecology Series: Volume 3 Harmful cyanobacteria. Springer: Dordrecht. Pp. 1-24.

Dignum, M., Matthijs, H., Pel, R., Laanbroek, H., and Mur, L. 2005. Nutrient limitation of freshwater cyanobacteria. In Huisman, J., Matthijs, H., and Visser, P. (2005). (Eds.) Aquatic Ecology Series: Volume 3 Harmful cyanobacteria. Springer: Dordrecht. Pp. 65-86.

Downing, J., Watson, S., and McCauley, E. 2001. Predicting cyanobacteria dominance in lakes. Canadian Journal of Fisheries and Aquatic Sciences, 58: 1905-1908.

Elser, J., Bracken, M., Cleland, E., Gruner, D., Harpole, W., Hillebrand, H., Ngai, J., Seabloom, E., Shurin, J., and Smith, J. 2007. Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. *Ecological Letters*, **10**: 1135-1142.

Gibbs, M. 2015. Assessing lake actions, risks and other actions. NIWA Client Report: NIWA2015-102 prepared for Bay of Plenty Regional Council.

Hamilton, D., Ozkundakci, D., Mcbride, C., Ye, W., Luo, L., Silvester, W., and White, P. 2012. Protecting the effects of nutrient loads, management regimes and climate change on water quality of Lake Rotorua. ERI Report No. 05. Report prepared for Bay of Plenty Regional Council.

Hamilton, D., McBride, C., and Jones, H. 2015. Assessing the effects of alum dosing of two inflows to Lake Rotorua against external nutrient load reductions: Model simulations for 2001-2012. ERI Report No. 49. Report prepared for Bay of Plenty Regional Council.

Hughes, B., Stephens, T., Snelder, T., and Kelly, D. 2016a. Lake FMUs for Northland Recommendations for Policy development. Land Water People Technical Report for Northland Regional Council. Pp. 90.

Huser, B., Egemose, S., Harper, H., Hupfer, M., Jensen, H., Pilgrim, K., Reitzel, K., Rydin, E., and Futter, M. 2016. Longevity and effectiveness of aluminium addition to reduce sediment phosphorus release and restorate lake water quality. *Water Research*, **97**: 122-132.

Jeppesen, E., Sondergaard, M., Jensen, J., Havens, K., Anneville, O., Carvalho, L., Coveney, M., Deneke, R., Dokulil, M., Foy, N., Gerdeaux, D., Hampton, S., Hilt, S., Kangur, K., Kohler, J., Lammens, E., Lauridnsen, T., Manca, M., Miracle, M., Moss, B., Noges, P., Persson, G., Phillips, G., Portielje, R., Romo, S., Schelske, C., Straile, D., Tatrai, I., Willen, E., and Winder, M. 2005. Lake responses to reduced nutrient loading – an analysis of contemporary long-term data from 35 case studies. *Freshwater Biology*, **50**: 1747-1771.

Jeppesen, E., Sondergaard, M., Meerhoff, M., Lauridsen, T., and Jensen, J. 2007. Shallow lake restoration by nutrient loading reduction – some recent findings and challenges ahead. *Hydrobiologia*, **584**: 239-252.

Lewis, W., Saunders, J., and McCutchan, J. 2008. Application of a nutrient-saturation concept to the control of algal growth in lakes. *Lake and Reservoir Management*, **24**: 41-46.

Loladze, I., and Elser, J. 2011. The origins of the Redfield nitrogen-to-phosphorus ratio are in a homoeostatic protein-to-rRNA ratio. *Ecology Letters*, **144**: 244-250.

McDowell, R. 2010. The efficacy of strategies to mitigate the loss of phosphorus from pastoral land use in the catchment of Lake Rotorua. AgResearch Report for Environment Bay of Plenty.

McDowell, R., Wilcock, B., and Hamilton, D. 2013. Assessment of mitigation strategies to mitigate the impact or loss of contaminants from agricultural land to fresh waters. AgResearch Client report for Ministry for Environment.

Morgernstern, U., Daughney, C., Leonard, G., Gordon, D., Donath, F., and Reeves, R. 2015. Using groundwater age and hydrochemistry to understand sources and dynamics of nutrient contamination through the catchment in Lake Rotorua, New Zealand. *Hydrological Earth Systems Science*, **19**: 803-822.

Moss, B., Jeppesen, E., Sondergaard, M., Lauridsen, T., and Liu, Z. 2013. Nitrogen, macrophytes, shallow lakes and nutrient limitation: resolution of a current controversy. *Hydrobiologia*, **710**: 3-21.

Paerl, H. 2008. Nutrient and other environmental controls of harmful cyanobacterial blooms along the freshwater-marine continuum. *Advances in Experimental Medicine and Biology*, **619**: 216-241.

Paerl, H., Xu, H., McCarthy, M., Zhu, G., Qin, B., Li, Y., and Gardner, S. 2010. Controlling harmful cyanobacterial blooms in a hyper-eutrophic lake (Lake Taihu, China): The need for a dual nutrient (N & P) management strategy. *Water Research*, **45**: 1973-1983.

Paerl, H., Xu, H., McCarthy, M., Zhu, G., Qin, B., Li, Y., and Gardner, W. 2011. Controlling harmful cyanobacterial blooms in a hyper-eutrophic lake (Lake Taihu, China): the need for a dual nutrient (N and P) management strategy. *Water Resources*. **45**:1973-1983

Paerl, H., Xu, H., Hall, N., Rossignol, K., Joyner, A., Zhu, G., and Qin, B. 2015. Nutrient limitation dynamics examined on a multi-annual scale in Lake Taihu, China: Implications for controlling eutrophication and harmful algal blooms. Journal of Freshwater Ecology, **30**: 5-24.

Ripp, B., Stephens, T., and Augustinus, P. 2016. Historic changes to water quality indicators in Poutō dune lakes. DairyNZ and University of Auckland Technical Report prepared for Northland Regional Council.

Rutherford, J., Pridmore, R., and White, E. 1989. Management of phosphorus and nitrogen inputs to Lake Rotorua, New Zealand. *Journal of Water Resources Planning and Management*, **115**: 431-439.

Schindler, D. 1977. Evolution of phosphorus limitation in lakes. *Science*, **195**: 260-262.

Schindler, D. 2012. The dilemma of controlling cultural eutrophication of lakes. *Proceedings of the Royal Society B*. doe:10.1098/rspb.2012.1032.

Schindler, D., Hecky, R., Findlay, D., Stainton, M., Parker, B., Paterson, M., Beaty, K., Lyng, M., and Kasian, S. 2008. Eutrophication of lakes cannot be controlled by reducing nitrogen input: results of a 37 year whole ecosystem experiment. *Proceedings of the National Academy of Science USA*, **105**: 11254-11258.

Scholes, P. 2013. Memorandum to Andy Bruere. RE: Rotorua Lakes 2012/2013 TLI Report.

Scholes, P. 2013. Trends and state of Rotorua major streams, 2013. Bay of Plenty Technical Report.

Scholes, P. and Hamill, K. 2016. Rotorua Lakes Water Quality Report 2014/15. Bay of Plenty Regional Council Environmental Publication 2016/06.

Sondergaard, M., Jensen, J., and Jeppesen, E. 2003. Role of sediment and internal loading of phosphorus in shallow lakes. *Hydrobiologia*, 506: 135-145.

Sondergaard, M., Jeppesen, E., Lauridsen. T., Skov, C., Van Nes, E., Roijackers, R., Lammens, E., and Portielje, R. 2007. Lake restoration: successes, failures and long-term effects. *Journal of Applied Ecology*, **44**: 1095-1105.

Smith, V. 2015. Comment on "Comment on 'Using groundwater age and hydrochemistry to understand sources and dynamics of nutrient contamination through the catchment into Lake Rotorua, New Zealand' by Morgenstern et al. (2015)" by Abell et al. (2015). *Hydrological Earth Systems Science Discussion*, **12**: C4492-C4501.

Smith, V., Wood, S., McBride, C., Atalah, J., Hamilton, D., and Abell, J. 2016. Phosphorus and nitrogen loading restraints are essential for successful eutrophication control of Lake Rotorua, New Zealand. *Inland Waters*, **6**:273-283.

Sterner, R. 2008. On the phosphorus limitation paradigm for lakes. *International Review of Hydrobiology*, **93**: 433-445.

Swales, A., Gibbs, M., Stephens, T., Olsen, G., Ovenden, R., and Costley, K. 2016. Sources of eroded soils and their contribution to long-term sedimentation in the Firth of Thames. NIWA Client Report for DairyNZ and Waikato Regional Council. NIWA Client Report No. HAM2016-001.

Tempero, G. 2015. Ecotoxicological review of alum applications to the Rotorua Lakes. ERI Report No.52 for Bay of Plenty Regional Council.

Tempero G., McBride C., Abell J., and Hamilton, D. 2015. Anthropogenic phosphorus loads to Lake Rotorua. Environmental Research Institute Report No. 66. Report prepared for Bay of Plenty Regional Council.

Vincent, W. 1981. Rapid physiological assays for nutrient demand by phytoplankton. I. Nitrogen. *Journal of Plankton Research*, **3**: 685-697.

Welch, E., and Cooke, D. 1999. Effectiveness and longevity of phosphorus inactivation with alum. *Lake and Reservoir Management Journal*, **15**: 5-27.

White, E., and Payne, G. 1978. Chlorophyll production in response to nutrient additions, by the algae in Lake Rotorua water. *New Zealand Journal of Marine and Freshwater Research*, **12**: 131-138.

White, E., Payne, G., Pickmere, S., and Woods, P. 1986. Nutrient demand and availability related to growth among natural assemblages of phytoplankton. New Zealand Journal of Marine and Freshwater Research, **20**: 199-208.

Wilcock, R., Biggs, B., Death, R., Hickey, C., Larned, S., and Quinn, J. 2007. Limiting nutrients for controlling undesirable periphyton growth. NIWA Client report for Horizons Regional Council.